Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-01 Room:313 Time:May 2 14:15-14:30

Science and Technology for Geothermal Frontier

TSUCHIYA, Noriyoshi[1*]

[1]Graduate School of Environmental Studies, Tohoku University

This project should cover multidisciplinary scientific fields such as geology, geochemistry, geophysics, water-rock interactions, rock mechanics, seismology, drilling technology, well logging technologies, reservoir engineering, and environmental science.

(a) Characterization of rock mass in BDT

Preliminary work by the Japanese researchers has revealed some of the behavior of the rock mass in the BDT, such as hydrothermal brecciation and presence of hydrothermally derived fracturing (HDF) (Hirano et al., 2003). However, fundamental understandings of key parameters such as the stress state, lithological structure, mechanical and compositional homogeneity, and thermal characteristics require much additional work. Laboratory tests would be the most effective means to obtain fundamental knowledge on the ductile rock mass in the initial stages of the project combined with analysis of core samples and pore water collected from an experimental borehole. This combination of laboratory and borehole data will generate, new knowledge on the rock mass and provide constraints on, and validation of the laboratory tests.

(b) Creation and control of the reservoirs

The HDF would create a brittle fracture network consisting of very fine fractures at grain boundaries, is created by cooling and depressurization from the borehole in the BDT. If a similar process operates during drilling then cooling of the ductile rock by the drill fluid may be expected to induce a grain-scale fracture network in the near field of the borehole during the drilling phase.

(c) Numerical simulation

To achieve sustainable energy production from EGSs in the BDT, it is essential to design the area of heat exchange between water and rock, and the risk of shortcut flow paths must be carefully evaluated. Simulators with capability to handle T-H-M-C behavior of the rock mass are expected.

Keywords: Geothermal

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-02 Room:313 Time:May 2 14:30-15:00

Deep seismic reflection profiling in geothermal area: case study of Shirasawa and Shichigashuku calderas

SATO, Hiroshi[1*] ; ABE, Susumu[2] ; UYESHIMA, Makoto[1]

[1]Earthquake Research Institute, The university of Tokyo, [2]Japex Geoscience Institute, Inc.

Along the Ou Backbone Range, northern Honshu, many piston-cylinder type calderas have been developed in Late Miocene to Pliocene. Recently, such calderas formed in late Miocene are focused as a possible resource of geothermal power plants. To obtain the physical data to estimate the sate of deep sited fluids and fractures is significance. Since late 90's, deep seismic reflection profiling was carried out to image the deeper extension of active faults. Some of the seismic lines are crossing such caldera (Sato et al., 2002a Tectonophys,: Sato et al., 2002b EPS). Here, we introduce the seismic sections and results of magnetotelluric investigation and discuss possible strategy for future's site survey.

Shirasawa caldera: The Shirasawa caldera is a piston-cylinder type caldera with 10-km-diameter and welded tuff and lake deposits are cropping out as caldera fill. By seismic reflection profiling using vibroseis trucks, low frequency strong reflectors are imaged 3 to 5 km beneath the caldera and estimated to be a possible evidence showing fluids. The estimation is well accord to the velocity structure obtained seismic tomography (Nakajima et al., 2006 EPS).

Shichigasuku caldera: This caldera is located southern part of Miyagi prefecture and shows piston-cylinder type. Across this caldera, deep seismic reflection profiling was performed in 2013 (Sato et al., 2013: JpGU). Also, magnetotelluric survey is carried out. P-wave velocity structure across the caldera shows low velocity part, which corresponds to the caldera fill, but does not suggest any characteristic feature showing existence of fluids. Magnetotelluric section suggest the distribution of vertical low resistivity zone connected slab to active volcanoes and low resistivity part which located in the md-to upper curst beneath caldera, showing the possibility of existence of fluids.

Significance of integrated geophysical exploration

To understand the physical state and material of deep sited portion beneath caldera, integrated research using several methods, active / passive seismic investigation, MT methods. Seismic reflection survey is not effective for rock unit, which does not have layering. However, it has a potential to evaluate the density of fractures and their pattern.

Keywords: geothermal area, caldera, seismic reflection profiling, magnetotelluric inversion, Shirasawa caldera, Shichigashuku caldera

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-03 Room:313 Time:May 2 15:00-15:15

Occurrence of rock/mineral fracture under the rapid decompression boiling condition of water

HIRANO, Nobuo[1*] ; AOSHIMA, Satoshi[1] ; KASAHARA, Naoya[1] ; OKAMOTO, Atsushi[1] ; WATANABE, Noriaki[1] ; TSUCHIYA, Noriyoshi[1]

[1]Graduate school of Environmental Studies, Tohoku University

In our previous water-rock interaction experiments under the various hydrothermal conditions using granite or artificial quartz samples, clear cracks or fractures in the samples were observed under the specific hydrothermal condition. We have named this phenomenon as ”Hydrothermally Derived Fracture (HDF)”. Understanding of this fracturing phenomenon may be useful for technological development of geothermal reservoir usage or clarification of vein formation mechanism in the Earth crust. In our previous experimental results, HDF were progressed under the high temperature and low-pressure condition. The result of detailed observation, it was thought that the thermal stress occurred with rapid cooling of rock/mineral sample surface by condensed vapor dew. Similarly, rapid decompression from the high-temperature/pressure state causes, the temperature drop by latent/sensible heat effect. Therefore, when the such rapid decompression was occurred around the rock/mineral samples, HDF may occur under the hydrothermal condition. And so, we attempted rapid decompression experiment from the over 20 MPa / 400?C hydrothermal condition. As a result, the fracturing in the samples was progressed clearly. Therefore, decompression fracturing is possible and the same phenomenon may arise subsurface of near the volcano or hotter and deeper crust with water.

Keywords: Hydrothermally Derived Fracture, Water-Rock Interaction, rapid decompression, granite, fracturing

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-04 Room:313 Time:May 2 15:15-15:30

Fracturing of granite under pore pressure and evolution of permeability

HAMASAKI, Shohei[1*] ; KATAYAMA, Ikuo[1]

[1]Department of Earth and Planetary Systems Science, Hiroshima University

Hot Dry Rock (HDR) geothermal power generation, which is included in Enhanced Geothermal System (EGS) is characterized by making artificial geothermal reservoir and this is different from conventional geothermal power generation. This system does not require natural hot water and steam. In this system, artificial reservoir is made by hydraulic fracturing in the basement due to high-pressure water injection, and water circulates in the system. Evolution of permeability is important factor in reservoir assessment. To assess this type of geothermal system, we measured effect of pore pressure compared with permeability during triaxial deformation experiment.

Aji granite was used as experimental sample, which is dense and fine, consists of mainly plagioclase, quartz, and biotite. Permeability was measured by intra-vessel deformation and fluid-flow apparatus (IVA) at Hiroshima University. Aji granite was saturated water before triaxial deformation experiments. Confining pressure (Pc) was fixed 20 MPa and pore pressure (Pp) was ranged from 0 MPa (undrain condition during triaxial deformation) to 15 MPa by 5 MPa at room temperature in triaxial deformation. The recovered samples after deformation experiments were fixed by resin and observed by polarizing microscopes and scanning electron microscope (SEM).We discussed relation between permeability and pore pressure - fracture strength from triaxial deformation experiments.

In original sample, permeability is $2.0X10^{-19}$ m^2 at Pc = 20 MPa. Permeability of fractured samples increased against that of original samples. Permeability proportionally increased from $2.5X10^{-18}$ m^2 at Pp = 0 MPa to $7.0X10^{-17}$ m^2 at Pp = 15 MPa. Fracture strength decreased with Pp decreased, from 400 MPa at Pp = 0 MPa to 350 MPa at Pp = 15 MPa. In fractured sample, there are macro fracture surface and microcracks.

The increase of permeability depends on pore pressure suggests that increase of microcrack width and acceleration of crack-connection and propagation in large Pp. And fracture strength relates crack sharps. Therefore, crack sharp and distribution are important parameter in assessment of permeability. We plan to further experiments which try to reproduce hydraulic fracture and high temperature condition.

Keywords: granite, pore pressure, permeability

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-05 Room:313 Time:May 2 15:30-15:45

The numerical study for behavior of fracture aperture associated with cold fluid flow

KANETA, Kousuke[1*] ; MUKUHIRA, Yusuke[1] ; SWENSON, Daniel[2] ; ITO, Takatoshi[1]

[1]Institute of Fluid Science, Tohoku University, Japan, [2]Mechanical and Nuclear Engineering Department, Kansas State University, USA

Power generation of geothermal power plant sometimes decreases due to reduction of reservoir pressure. Reinjection of used geothermal fluid/cold fluid into the reservoir is conducted in several geothermal power plant to keep/recover the reservoir pressure. It is required for recharge of reservoir pressure that appropriate condition of reinjection in terms of injection pressure, amount of injected fluid, and heat balance. On the other hand, it is empirically observed at some of the geothermal field that amount of injected fluid increases when lower temperature fluid is injected. In this research, we investigated relationship between temperatures of cold fluid and fracture aperture, using numerical simulation.

We conducted numerical simulation for the change in fracture aperture when cold fluid flows into the fracture, using 2D FEM code ″ GEOCRACK2D ″ (Swenson et al., 1995). We set the condition that cold fluid was injected into a single fracture within high temperature rock mass. In this simulation, cold fluid flowed from center of fracture to edge of fracture. Fluid pressure was 1 MPa at center of fracture and 0 MPa at edge of fracture. This given pressure condition made fluid flow from center of fracture to edge of fracture. Initial temperature of rock mass was 300 ℃ and that of cold fluid was 100 ℃. Initial stress condition was 20 MPa in x direction and y direction.

As a result of simulation, the fracture aperture increased with time although 20 MPa of normal stress worked on the rock mass and fluid pressure was at most 1 MPa. It was also simulated that the rock mass around the fracture was cooled down by cold fluid and cooled area extended with time. Normal stress on the fracture decreased. The area where normal stress decreased extended over time.

These results can be interpreted that cooling of rock mass by cold fluid caused thermal shrinkage of rock mass, which decreased normal stress on the fracture surface. Finally, the fracture aperture became large, suggesting increasing in permeability.

We also conducted the simulation for the effect of difference in initial temperature between rock mass and cold fluid. We compared the change in fracture aperture about four temperature difference conditions. Fluid flow, fluid pressure, temperature of rock mass and initial stress condition were same with first simulation. Temperature of cold fluid was 100 ℃, 150 ℃, 200 ℃ and 250 ℃.

As a result of simulation, the fracture aperture increased drastically when the temperature difference between rock mass and cold fluid was bigger than 150 ℃. The fracture aperture slightly increased when the temperature difference is smaller than 100 ℃. The bigger temperature difference was, the earlier fracture aperture opened. The results of simulation suggested that there was the critical value in temperature difference between 100 ℃ and 150 ℃. It was summarized that the fracture aperture increased and that the fracture permeability became large when the temperature difference was bigger than the critical temperature difference.

Keywords: Geothermal reservoir, Fracture, Aperture, Thermal elasticity, Thermal shrinkage, Reinjection

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-06 Room:313 Time:May 2 15:45-16:00

Slip-able area: New index to evaluate the fault area under critical state based on microseismic data at stimulation

MUKUHIRA, Yusuke[1*] ; ASANUMA, Hiroshi[2] ; HARING, Markus[3] ; ITO, Takatoshi[1]

[1]Institute of Fluid Science, Tohoku University, [2]AIST, [3]Geo Explorer Ltd.

Unexpected occurrence of felt earthquake has been big issue as critical environmental burden associated with geothermal development and other energy extraction. The magnitude of seismic events induced by fluid stimulation is generally small enough to be perceived on the ground. However, at the Basel, Switzerland, some of the events had large magnitude, resulting in the shutdown of engineered geothermal system (EGS) project. Our previous study has revealed the fundamental characteristics and the trigger mechanisms of the large event at Basel. However, we have not reached full understanding of physics of the large events, which enable us to control or manage the magnitude of induced events.

Concept of Slip-able area

Our previous study suggested that the dynamic behavior of pore pressure especially propagation of pressure at the shut-in correlate the event magnitude because many of large events occurred at the shut-in phase in Basel. The pore pressure gradient should exist from the well head to the pressure front during the stimulation. At the shut-in when pumping is stopped, the pressure source despairs and subsequently the pressure gradient may become small with time. Finally, the pore pressure in the reservoir will go back hydrostatic state uniformly. In the relaxation process of the pore pressure gradient, it can be expected that the pore pressure at the far field from the well might slightly increase to average pore pressure increase in whole reservoir. Pore pressure increase at the front of the stimulated zone may put large part of the fault plane into near critical state. In contrast, only some part of the fault plane may become critical state, when the pore pressure increases with the pressure gradient. This is the expected scenario for occurrence of the large event at the shut-in.

So, in this study, we originally defined new concept of Slip-able area, which describes the summation of fault areas in study area, under critical state during/after the stimulation. The informations used in estimating Slip-able are given by the detailed analysis of microseismic events and stress information. Slip-able area can provide the information of the potential fault area which can have shear slip at semi real time. Slip-able area can be directly converted into the event magnitude, suggesting it is also available to the risk assessment of the large event.

Methodology of estimation for Slip-able area

We propose the methodology to estimate Slip-able area as follows.

1.Determine the number of the potential fracture within a given rock volume from microseismic data at the first stage of the stimulation.

2.Characterize the size of the fractures from source parameter of microseismic events and their critical pore pressure for shear slip.

3.Divide the reservoir area into a number of the block with the same size of step1.

4.Determine the stimulated volume in three dimensions by the divided block and information on occurrence of microseismic events.

5.Infer the number of the fracture in a stimulated volume determined in step 4.

6.Estimate maximum increase in pore pressure at given time in each block of stimulated volume.

7.Identify the fault area of the fracture under critical state using the information assummed in step 2.

8.Integrate all fault area of the fractures identified in step 7.

We have to note that the methodology shown above includes some steps with much difficulty or impossible because determination of critical pore pressure is based on the information on orientation of fracture plane and stress information in study area. These informations are not available in many of the geothermal field. Estimation of fault area also required high quality data set of microseismic events. In these cases, it can be valid for simplification to use appropriate constant values like b value as a substitute for characterizing of fault size.

Keywords: Microseismicty, Felt earthquake, Magnitude, Fault area, Risk assessment, Basel

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-07 Room:313 Time:May 2 16:15-16:30

Hydration of crust through brittle fractures: Example from Sor Rondane Mountains, East Antarctica

UNO, Masaoki[1*] ; OKAMOTO, Atsushi[1] ; TSUCHIYA, Noriyoshi[1]

[1]Graduate School of Environmental Studies, Tohoku University

Arc lower crust is expected to be amphibolite from its seismic velocity, and such lithology contains abundant hydrous minerals. However, the amount and mechanisms for supply of H_2O fluid to arc crust are not well constrained. Pervasive flow and channeling flow are the two mechanisms for the transfer of fluid in the crust. As grain boundaries are closed for crustal P-T condition, channeling flow accompanied by brittle fracture is expected. To investigate the role of brittle fracture to the supply of H_2O fluid for crust, crust-melt hydration reaction was investigated at Sor Rondane Mountains, East Antarctica.

In the survey area, biotite-hornblende-peridotite is intruded by numerous granitic brittle dykes, and reaction zones occurs at the boundaries (Fig. 1). The mineral assemblages indicate that the reaction has occurred under lower crustal P-T condition, thus the area is suitable for investigating both mechanical and physical aspects of fluid-rock interactions under the lower crustal condition. Four reaction zones are identified from the granitic dyke to the host rock as follows:

i) granitic dyke
[quartz + plagioclase + K-feldspar + biotite + rutile + zircon ± muscovite]
ii) hornblende-tremolite zone
[hornblende + tremolite ± quartz ± apatite ± biotite]
iii) tremolite-biotite zone
[tremolite + biotite + spinel ± hornblende ± pyroxene]
iv) biotite-hornblende-peridotite
[olivine + orthopyroxene + biotite + hornblende + Cr-spinel ± magnetite ± apatite]

Those reaction zones are product of hydration reactions of host peridotite with H_2O liberated from granitic melt. From plagioclase in granitic dyke and adjoining hornblende, the temperature of those reactions is estimated[1] to be 700 ^{o}C.

The amount of H_2O liberated from the granitic melt will be quantified by the modes of hydrous minerals formed at the reaction zones. Accordingly, the amount of H_2O supplied thorough hydrous melts, and the mechanisms for transport of H_2O and hydration of the crust will be discussed.

Keywords: geofluid, brittle fractures, melt, hydration reaciton, fluid-rock interaction, Antarctica

Fig. 1 Biotite-hornblende-peridotite (brown) intruded by granitic dykes (white), Sør Rondane Mountains, East Antarctica. Note that reaction zones occur at the boundary: green or black layers are hornblende-tremolite zone and grey to reddish brown layers are tremolite-biotite zone.

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-08 Room:313 Time:May 2 16:30-16:45

Composite basaltic andesite lava in Iwanuma (Miyagi, Japan): Differentiation along segregation veins and columnar joints

KIMOTO, Kazuki[2] ; ISHIWATARI, Akira[1*]

[1]Center for NE Asian Studies, Tohoku Univ., [2]Dept. Earth Sci., Grad. Sch. Sci., Tohoku Univ.

Occurrence of thin (3-5 m) composite lavas with central phenocryst-rich layers was reported by Kuno (1950; JGSJ, 56, 167-172) and others, but we found very thick (>110 m) composite lava comprising a single cooling unit (with penetrating columnar joints) but consisting of some distinct chemical layers with segregation veins at the layer boundaries.

The basaltic andesite lavas of the middle Miocene age (15˜13 Ma) occur in Iwanuma City, Miyagi Prefecture, Japan. Thickness of the main lava flow measures more than 110 m. Vertical columnar joints of 1 or 2 m intervals are well developed through the outcrop. This lava flow is a composite lava flow with the lower layer (0˜42 m from bottom) having rather felsic composition (SiO_2 55 wt. %) and the upper layer (45˜110 m from bottom) having more mafic compositions (SiO_2 52˜54 wt. %).There are no macroscopic differences between the two layers, but the size of plagioclase in the nearly holocrystalline groundmass of the upper layer is larger (<0.5 mm) than that of the lower layer (<0.3 mm) under the microscope. Red clinker is seen at the bottom of the outcrop, but the top of the flow has been eroded.

Many horizontal segregation veins are observed at the limited portions in the intervals of 6˜14 m (lower vein zone), 45˜64 m (central vein zone) and 80˜95 m (upper vein zone) from bottom. The lower veins are 1 mm in thickness at intervals of 1˜10 cm, have glassy structure and contain plagioclase and augite. The central veins are 5˜15 mm in thickness at intervals of 10˜15 cm at 45 m from bottom and 3˜5 mm at intervals of 5˜15 cm at 52˜64 m from bottom, have crystalline structure and contain plagioclase, pigeonite and subcalcic augite. The upper veins are 3˜5 mm in thickness at intervals of 5˜7 cm and have similar structure and mineral assemblage to the central veins. The segregated melt of the central veins forms after the approximately 70 % crystallization of the host magma. The segregation veins are apparently formed by the migration of the residual melt into the subhorizontal fractures (platy joints) which resulted from the shear deformation and cooling contraction in the crystallizing lava flow, especially near the bottom of the flow and at the bottom part of the flow and relatively mafic layers in the upper part of the composite lava flow. Rare en echelon segregation veins are the evidence for shear deformation.

The columnar joints always perpendicularly cut segregation veins, and the rocks adjacent to the columnar joint plane show low density and increase of vesicles in comparison with the rocks in the middle of the column. This suggests that columnar joints developed far later than the segregation-filled platy joints, but some melt was still present at that time so as to allow its vesiculation promoted by the columnar joint fracturing.

Keywords: composite lava flow, segregation vein, platy joint, colunmar joint, basaltic andesite, crystallization differentiation

Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

SMP48-09 Room:313 Time:May 2 16:45-17:00

The formation of the permeable-impermeable boundary within the Earth's crust revealed by silica precipitation

SAISHU, Hanae[1*] ; OKAMOTO, Atsushi[1] ; TSUCHIYA, Noriyoshi[1]

[1]AIST, [2]Tohoku University

Silica is one of the dominant constituents of the Earth's crust. The permeable-impermeable boundary corresponds to the brittle plastic transition at 300-450 C [1]. Ubiquitous occurrence of quartz vein is one of the evidences that the spatial and temporal variations in permeability within the Earth's crust are affected by silica precipitation in aqueous fluids. However, the role of silica-water interaction on fracture permeability is still unclear.

The Kakkonda geothermal field, Japan, has the well WD-1a that penetrated the boundary between the hydrothermal convection zone and the heat conduction zone [2]. Calculation of quartz solubility along the well WD-1a revealed that (1) the depth of a local maximum of quartz solubility correlates with that of the strong reflector in seismic data at 350 C isotherm [3], and that of a maximum of fracture numbers revealed by the logs of FMI [4], and (2) the depth of a local minimum of quartz solubility correlates with that of the permeable-impermeable boundary, in either case of hydrostatic or lithostatic conditions [5]. These results indicate that (1) the preservation of open fractures at the margin of the Kakkonda granite is controlled by dissolution of quartz, and (2) the quartz precipitation could occur from both downwards- and upwards-moving fluids, which could divide the hydrothermal convection zone and the heat conduction zone.

The hydrothermal experiments of temperature dependence of silica precipitation were conducted at 24 and 31 MPa and 170-430 C, by using the solution made by dissolution of granite. The large amount of silica precipitation occurred only in the supercritical conditions of water (>390 C). Strong temperature dependence can be explained by the homogeneous nucleation of quartz in the surface energy of quartz of 130 mJ/m^2 [5].

The results of the calculation of silica solubility at the Kakkonda geothermal field and the hydrothermal experiments of silica precipitation suggest that rapid quartz precipitation via nucleation could occur when fluids are brought to the depth in the supercritical conditions of water. The forming and sustaining the permeable-impermeable boundary within the Earth's crust could be controlled by precipitation of silica minerals.

References
[1] Scholz (2002).
[2] Doi et al. (1998) *Geothermics*, **27**, 663-690.
[3] Matsushima et al. (2003) *Geothermics*, **32**, 79-99.
[4] Muraokaet al. (1998) *Geothermics*, **27**, 507-534.
[5] Saishu et al. (in press) *Terra Nova*.

Keywords: Silica precipitation, Quartz solubility, Permeable-impermeable boundary, Hydrothermal experiment